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13. ABSTRACT *(Maximum 200 words)*

In this program the Microphysics Laboratory has been successful in:

1) identifying the presence of microtwins in HgCdTe(111)B grown by MBE which are limiting device performance and yield,
2) determining their relation with the structural and electrical properties of the epilayer
3) understanding their formation mechanism
4) controlling and eliminating their formation through stringent control of the growth parameters, and
5) in formulating the hypothesis that impurities, very likely diffusing from the substrate, are present in the epilayer.

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INFLUENCE OF DEFECTS IN HgCdTe GROWN BY MOLECULAR BEAM EPITAXY (MBE) ON ELECTRICAL DEVICES

CONTRACT # DAAL03-87-K-0092

JEAN-PIERRE FAURIE
PRINCIPAL INVESTIGATOR

FINAL REPORT

I. INTRODUCTION

Although HgCdTe was known to be the most important semiconductor for IR detection, at the initiation of this contract, there was little information about the relationship between defects, physical properties and diode performance. This statement was true not only for MBE grown HgCdTe but also for LPE and MOCVD grown epitaxy. The first goal of this program was to identify the defects formed during the MBE growth. The second was to control and to prevent, if possible, their formation. The third was to establish relations between their presence and the physical properties of HgCdTe MBE epilayer. These objectives were those of the Microphysics Laboratory at Chicago. In parallel, Rockwell International Science Center was supposed to be involved in device fabrication to assess MBE HgCdTe material and fabrication limits.

In 1988 it appeared very clearly, after fabrication and testing the first photodiodes, that microstructural defects present in HgCdTe layers grown in the (111)B orientation have an adverse effect on diode performance and have a determining influence on structural and electrical properties as well as on the intrinsic and extrinsic doping of HgCdTe. Control of the twinning during growth in the (111)B orientation has been a major challenge as will be discussed hereafter.

II. PRELIMINARY CHARACTERIZATION OF MBE GROWN HgCdTe THROUGH PHOTODIODE FABRICATION

In order to assess the quality of HgCdTe materials grown by MBE and its suitability for IR photodiodes the first action in this contract has been to fabricate p-n junctions using the ion implantation technique. The devices have been fabricated and tested by Rockwell on HgCdTe (111)B layers grown by the Microphysics Laboratory on CdTe (111)B substrates. These junctions have been made on as-grown p-type layers, 12 μm thick. The diode dark currents in the diffusion regime and the spectral response attest to the excellent uniformity in composition of the layer. We have also established that in the diffusion regime, the data can be explained by the ideal diode equation with electrical parameters measured on the as-grown MBE layers.

The problems at low temperature are complex because factors in material and fabrication are independent and the dark currents are likely dominated by grown induced and process induced defects difficult to separate. The results have been detailed in the paper.

"Characteristics of p-n junctions fabricated on HgCdTe epilayers grown by MBE," Applied Physics Letters 52, 2151 (1988). From this preliminary work we concluded that devices fabricated by current state-of-the-art MBE technology were of comparable performance to those fabricated by conventional growth techniques in the diffusion regime of operation.

Several layers have been implanted but it turned out that for most of them only a few diodes were working. We concluded that high EPD (high 10^6 cm^{-2}) due to twinning was responsible for low yield. These results obtained in 1987 and early 1988 have triggered our effort related to the twinning problem as explained in the introduction and detailed in part III.

III. MICROTWIN FORMATION IN THE GROWTH BY MBE OF HgCdTe IN THE (111)B ORIENTATION

One of the major problems encountered in the growth of HgCdTe when a vapor phase technique such as MBE is used is the formation of microstructural defects such as microtwins and hillocks. From the current work of different laboratories involved in the fabrication of IR photodiodes it appears that the presence of twins is highly deleterious for photodiode performances. Actually it is thought that what is detrimental to diodes is the existence of dislocations associated with the twins. An etch pit density count (EPD) of $1x10^6$ cm^2 or less is considered necessary to achieve good photodiodes. The (111)B orientation is particularly vulnerable to the twin formation but the other orientations such as (211)B and (311)B are also sensible to twinning. In addition, we think that hillock formation observed during the growth in the (100) orientation, which is highly detrimental to MIS structure, is also twin related. Therefore, identifying and solving the twinning problem was one of our major concerns during the current contract.

The (111)B orientation despite its easiness to form twins is a very important orientation because the mercury consumption is lower than in the (100) orientation,[1] surfaces and interfaces usually are very smooth in the (111)B plane, CdTe and CdZnTe substrates are obtained in high yield in this orientation and it is so far the most favorable orientation to grow on GaAs(100) substrates. Detailed investigation involving electron microscopy, cathodoluminescence (CL) chemical etching, X-ray diffraction as well as electron channeling pattern (ECP) have revealed the presence of twins in CdTe and HgCdTe epilayers grown in the (111)B orientation.

In zinc-blende structures the twinning illustrated in Fig. 1 is observed very often. It is a rotational type of twin corresponding to a 180° rotation about the [111] normal direction. The stacking of (111) plane in the fcc structure changes from abc type I configuration to acb type II configuration. The two stackings are equivalent, the changes require very low formation energy since Cd(Hg) - Te bonds are preserved. This change can therefore occur several times during growth. This kind of twinning is sometimes called lamellar twinning.

During the first step of epitaxial growth, islands can be formed which will grow and coalesce to form the epitaxial film. These islands may be of type I or type II configuration since they are energetically almost equivalent (Fig. 2). Therefore, twin boundaries will exist after island coalescence and twin domains will grow in a columnar form. This kind of twinning which is also of a rotational type is sometimes called double positioning twinning.

These two kinds of rotations can coexist in the crystal but one or both can disappear during the growth. It is difficult to observe rotational twins during the MBE growth by electron diffraction because the streaked (2D) patterns of type I or type II configurations identical RHEED patterns and sometimes roughening of the surface, which allows 3D diffraction, is not detected. The twinned domains present in the crystal are visible on the surface of the crystal under the scanning electron microscopy or cathodoluminescence investigations on the form of close loops as illustrated in Fig. 3 for a CdTe layer. Etch pit density carried out on such a twinned HgCdTe(111)B epilayer not only will allow the EPD determination but will also reveal the presence of twin boundaries as illustrated in Fig. 4. It can be seen that the triangular pits are rotated by 180° from one domain to another confirming the existence of twins.

Electron channeling pattern (ECP) can also help in the discovery of twins Fig. 5a, b shown two simulated ECP of a twin-free and a twinned crystal. The (113) plane family has a 3-fold symmetry illustrated in a form of a regular triangle in a twin-free configuration whereas in a twinned configuration a second inverted triangle is revealed. Fig. 5 shows the ECP pattern of a twinned CdTe layer similar to the one illustrate in Fig. 5.

These two kinds of twinning can occur in both CdTe and HgCdTe. In HgCdTe, however, due to the high mercury flux used during the growth we think that a third kind of twinning illustrated in Fig. 6 can occur. This reflection type twin is formed by a mirror reflection with respect to the (111) twin plane. This produces a change in the polarity of the

face by creating an antiphase boundary. As shown in Fig. 6, Hg-Hg bonds which usually require high formation energy might occur at the plane of the reflection twin when the Hg flux is too high. This twinning does not occur across the entire area of the wafer therefore the growing surface exhibits (111)B and (111)A orientation simultaneously. The growth rate of (111)B and (111)A faces being different[1] a surface roughening allowing the observation of extra dots in the RHEED pattern is associated with this kind of twinning.

During the growth of HgCdTe in the (111)B orientation the presences of extra dots due to twinning are observed when the Hg flux is too high for a selected substrate temperature. A decrease in the Hg flux or an increase in the substrate temperature produce rapidly a change in the RHEED pattern, extra dots are disappearing and the spotty pattern is transformed into a streaky one. This is expected since a (111)A face is a Hg terminated unstable face requiring a high Hg flux. A new antiphase boundary with Te-Te bond is created reversing the (111)A to a (111)B face.

Fig. 7 is a TEM picture of a HgCdTe(111)B layer grown on a CdTe(111)B/GaAs(100) substrate. It can be seen that the CdTe layer grown on GaAs is full of lamellar twins. At the initiation of HgCdTe growth twins were visible on the RHEED pattern. The growth conditions were kept the same for a while and then the substrate temperature was increased by 5°C. Almost instantaneously the RHEED changes for a twin-free related electron diffraction pattern. The TEM micrograph confirms our in-situ observation since a twin is visible in the HgCdTe layer and the position where the twin has disappeared corresponds very precisely to the change in the substrate temperature and the RHEED pattern. High resolution transmission electron microscopy (HRTEM) has not been able to confirm the "reflection" nature of the twin since it is extremely difficult to reveal fine details of atomic structure. However, it is highly probable that this kind of twinning occurs when the Hg flux is too high.

From these investigation it is concluded,

1. HgCdTe grown by MBE in the (111)B orientation are twinned if stringent growth conditions are not applied.
2. HgCdTe(111)B twinned layers exhibit double crystal X-ray rocking curves larger than 100 arcsec and EPD of 10^6 to 10^7 cm^{-2}. This density of extended defects limits device performance and yield.

3. At a fixed growth temperature it has been reported before that when Hg flux is slightly too low polycrystalline growth occurs. In this work we have observed that when the Hg flux is slightly too high microtwins are formed. It appears that the Hg flux window is narrow for a fixed growth temperature.

IV. GROWTH OF HgCdTe(111)B TWIN-FREE EPILAYERS

In order to control microtwin formation it is extremely important to carefully control each step of the growth process. The surface of the substrate should be prepared under very clean conditions and within the proper temperature range. The growth of the CdTe buffer layer has also to be grown under optimized growth conditions in order to obtain the highest crystal quality. If the growth occurs on a lattice matched CdZnTe substrate the growth of a CdTe buffer layer is not absolutely necessary.

The growth of twin-free (111)B HgCdTe represents a real challenge. In addition to rotational twins, reflection twins have been observed as discussed in part III. First of all the substrate and the buffer layer should be twin-free. Therefore, great care has to be taken during substrate screening, substrate preparation and buffer layer growth as discussed before. The same precautions have to be observed during the first steps of the HgCdTe growth in order to prevent double positioning twin formation. During the growth we have seen that an increase in the Hg flux (F_{Hg}) or a decrease in the surface substrate temperature (T_{SS}) can trigger the formation of an antiphase boundary. On the other hand a decrease in the Hg flux or an increase in the substrate temperature will induce a polycrystalline growth. The window for the growth is very narrow and we have determined that for suitable growth conditions the stability during the growth should be of $\pm 2.5\%$ on the F_{Hg} and $\pm 0.5°C$ on T_{SS}.

The control of the substrate temperature T_S is the most difficult task because what has to be controlled is, in fact, the temperature of the surface T_{SS}. We have verified that the temperature indicated by the thermocouple located in the back of the substrate which rotates

1) does not give an accurate reading of the substrate temperature, and
2) does not account quickly for the surface temperature change.

This is illustrated in Fig. 8 showing that in order to keep T_{SS} constant which is an imperative requirement the back thermocouple T_B reading will <u>increase</u> by 30-40°C. In other words, if T_B

is kept constant, which is the usual way to proceed, the real surface temperature T_{ss} will decrease by 30-40°C. Then the Hg flux kept constant will become too high since the Hg sticking coefficient changes drastically with temperature and reflection twins visible on the RHEED pattern will be formed. From these experiments it appears that the control of the surface substrate temperature T_{ss} which is key parameter and should be kept constant within 1°C is an extremely difficult task.

The used of an IR pyrometer does not represent either an ideal solution at the start of the growth. When T_{ss} is kept constant at 190°C, by using a front thermocouple, at the initiation of HgCdTe growth a jump of approximately 25°C (in our MBE configuration) occurs in the pyrometer reading T_P due to scattered IR radiation primarily from the hot CdTe cell as illustrated in Fig. 8. Immediately T_P falls steeply due to both the rapid decrease in reflectance of the block and the fall toward the first minimum in the interference pattern related to the presence of a thin HgCdTe layer. Once the first minimum is reached T_P rises toward the next maximum. Several more oscillations of decreasing amplitude follow. After about 40 minutes of growth, the oscillations are almost completely gone. At this point T_P is approximately 15°C higher than the reading before growth. This increase is primarily due to emitted radiation since emittance increases as cadmium composition decreases. During this time the back thermocouple T_B reading has increased by 30-40°C. Since a front thermocouple cannot be left during conventional growth using rotation, a double control involving a back thermocouple and an IR pyrometer along with the knowledge based on tedious experiments identical to the one described before, is currently utilized in the Microphysics Laboratory. These investigations have resulted in a much better control of T_{ss} and F_{Hg}. This first improvement has been confirmed by the growth of twin-free HgCdTe(111)B presented hereafter.

V. HgCdTe(111)B: COMPARISON BETWEEN TWINNED AND TWIN-FREE LAYERS

$Hg_{1-x}Cd_xTe$ twinned layers grown by the Microphysics Laboratory in the (111)B orientation usually exhibits a p-type character with hole mobility approaching or even exceeding 10^3 cm^2 V^{-1} s^{-1}[2] and excess carrier lifetime in the 20-100x10^{-9}s.[3] An excellent electrical mobility is often considered to be associated with an excellent quality. It turns out that it is not

precisely the case here.

All the layers exhibiting 10^3 $cm^2V^{-1}s^{-1}$ have been investigated using X-ray diffraction. X-ray rocking curve recorded for the (422) reflection have shown, for all of them, 6 peaks before a 360° rotation the sample about the <111> axis while only three peaks should be observed in a twin-free epilayer. These findings were confirmed by ECP experiments. The first though was that the presence of twins does not degrade the hole mobility. In order to confirm this, two HgCdTe epilayers (x=0.25) have been grown under the same growth condition except that the Hg flux was increased several times for several minutes during the growth of layer A whereas for layer B the twin-free growth conditions have been applied. X-ray diffraction confirmed that layer B is twin-free and layer A is twinned. Both layers have a p-type character, however, whereas layer A exhibits a hole mobility of 900 $cm^2v^{-1}s^{-1}$ layer B has only a hole mobility of 300 $cm^2V^{-1}s^{-1}$ at 23K. All the twin-free p-type layers grown so far have a hole mobility not exceeding 500 $cm^2V^{-1}s^{-1}$.

In addition the carrier concentration N_A-N_D for p-type twinned layers has been consistently found to be in a the 1-5x10^{16} cm^{-3} and from the Hall data curve fitting N_A has been calculated to be in the 5-8x10^{16} cm^{-3} range as reported before.[4] P-type twin-free layers display a much lower carrier concentration: N_A-N_D is in the low 10^{15} cm^{-3} range. The decrease in N_A-N_D is so drastic in twin-free layers that many of them turned out to be n-type. Hence the lower hole mobility in twin-free layers cannot be explained by an increase in scattering due to a large acceptor concentration since it is the opposite. Therefore, it is concluded that

1) electrically active acceptors are associated with the presence of twins in HgCdTe. and
2) a relationship exists between the high hole mobility and the presence of twins in HgCdTe.

$Hg_{1-x}Cd_xTe$ grown at 200°C under Te-rich conditions, such as MBE and under thermal equilibrium conditions should produce an intrinsic hole concentration due to Hg vacancy in the mid 10^{15} cm^{-3} range.[5,6] Hence it appears that in the (111)B orientation twinned layers have a p-type doping level exceeding the one expected from growth under thermodynamical equilibrium at the same temperature. In addition, the fact that fast low temperature isothermal (mercury-rich) anneals make the (111)B materials even more p-type leads us to believe that extended

defects are mostly responsible for the electronic activity in the as-grown material. The increase in the acceptor level could be explained by the presence of numerous (111)A planes in the twin boundaries and antiphase boundaries. As reported before[1] a (111)A plane which is Hg terminated is very unstable and thus should have a Hg-vacancy density higher than the one thermodynamically calculated for a bulk crystal.

Concerning the high hole mobility no clear explanation has yet been found. However, it is possible that with the excess of mercury, which triggers the formation of Hg-rich antiphase boundaries, Hg-rich alloy zones formed in the crystal. Therefore, numerous Type III (semimetal-semiconductor) interfaces exist within the crystal. It has been discovered and explained[7,8] that a high hole mobility due to light-heavy hole effective mass is associated with Type III interface. Hence the measured Hall mobility in these non-homogenous crystals would average the high hole mobility associated with Type III interface holes and the low hole mobility of the bulk.

Another important difference related to etch pit density (EPD) and reported in Table I has been found between twinned and twin-free layers. The percentage of twins has been qualitatively determined from X-ray diffraction by comparing the intensities of twin-related peaks with crystal lattice peaks.

TABLE 1

$Hg_{1-x}Cd_xTe$ sample#	x	Twin	EPD(cm^{-2})
935	0.24	50%	$8x10^6$
933	0.33	10%	$5x10^5$
932	0.21	0	$8x10^4$

One can see that by eliminating twins, EPD can drop tremendously indicating a drastic improvement in the crystal quality unexpectedly associated with a decrease in the hole mobility measured by Hall in p-type layers.

Very long isothermal annealings have been performed on twinned and twin-free (111)B HgCdTe layers. The results in both cases are very similar in their inconsistency. Mixed

conduction which can be explained by a non-uniformity in the doping along with the presence of acceptors and donors is very often observed. P-type anneal, on the other hand, very often results in p-type layer with very good electrical characteristics. The only possible conclusion that we have reached concerning the understanding of isothermal anneal is that it is controlled by various impurities which have not been yet identified.

Table 2 provides a brief summary of the main differences between (111)B twinned and twin-free layers grown by MBE.

TABLE 2

	Twinned Layer	Twin-Free Layer
Conduction type	p-type	p-type - n-type or mixed conduction
p-type layers		
N_A-N_D (as-grown)	$2.5x10^{16}$ cm^{-3}	$1-2x10^{15}$ cm^{-3}
Hole mobility	800-1600 cm^2/vsec	300-500 cm^2/vsec
EPD	10^6-10^7 cm^{-2}	10^4-10^5 cm^{-2}
Residual doping level after isothermal annealing	non reproducible results ($5x10^{15}$-$2x10^{16}$ cm^{-3}) mixed conduction very often	
p-type anneal	p-type	p-type

VI. GROWTH IN (211)B ORIENTATION

The progress accomplished in the growth in the (111)B orientation has been used to control in a better way the growth in different orientations. We have devoted our recent efforts in the growth along the <211> azimuth where the twinning problem does not appear as severe as in the (111)B. The layers grown in the (211)B orientation under the stringent growth control previously discussed exhibit excellent properties. As an example the layer #1008 has the

following as-grown characteristics:

x =	0.18
thickness:	16.2 μm
N_d-N_a:	1.9×10^{14} cm^{-3} at 15K
electron mobility:	1.1×10^{6} $cm^2V^{-1}s^{-1}$ at 15K
lifetime:	9×10^{-6} sec at 250K (peak)
	2.2×10^{-6} sec at 77K

After isothermal anneal this layer exhibits an n-type character but with a much lower mobility which is a sign of compensation. There are two hypotheses:

1) impurities are incorporated during the MBE growth process, and/or

2) impurities diffuse from the substrate.

Since isothermal anneal occurs at about the same temperature (200-250°C) than the growth temperature it is very unlikely that impurities present in the as-grown layer have been activated during the anneal. The control of the doping being so important this should be investigated very thoroughly.

VII. SUMMARY

The main task in this program has been in the identification, role, control and elimination of microtwins in HgCdTe grown by MBE in the (111)B orientation. P-n junctions fabricated at the initiation of the contract on HgCdTe epilayer grown by MBE on CdTe(111)B substrates have shown comparable performance to those fabricated by conventional growth techniques in the diffusion regime of operation. The diode dark currents and the spectral response attest to the excellent uniformity in composition of the layer. However, as in conventional technologies, the device characteristics were not uniform at low temperatures. Based on structural property analysis we have concluded that microstructural defects such as microtwins were playing a major role in device performance and yield limitation.

Rotational twins are easily formed in CdTe(111) and HgCdTe(111) epilayers. In addition, reflection twins which are related to a change in the Hg pressure and/or the surface substrate temperature can be formed during the growth of HgCdTe. Careful substrate preparation with proper thermal cleaning can prevent the formation of double positioning twins.

To avoid the formation of reflection twins a stringent control in the stability of Hg ($\pm 2.5\%$), growth rate and surface substrate temperature ($\pm 0.5\%$) is required, which is very difficult when the substrate is rotating. Such control has been achieved in the Microphysics Laboratory and twin-free CdTe and HgCdTe(111)B layers have been grown.

A comparison between HgCdTe twinned layers and twin-free layers shows that electrically active acceptors along with high hole mobility are associated with the presence of micro twins in HgCdTe. Etch pit density as low as 8×10^4 cm^{-2} has been counted on twin-free HgCdTe layers which are two orders of magnitude lower than EPD's of twinned layers.

The MBE growth of twin-free HgCdTe(111)B layers while the substrate is rotating represents a major accomplishment in the field. The progress achieved in the growth in the (111)B orientation has been used to control in better way the growth in different orientations. Layers grown in the (211)B orientation under the stringent growth control required for twin-free growth in (111)b exhibit outstanding properties.

Since HgCdTe material during junction formation and device fabrication process experiences high temperature steps we have carried out both isothermal and p-type anneal. Whereas p-type anneal usually results in p-type layers with very good electrical properties, isothermal anneal usually produces epilayers with mixed conduction. This behavior which has been observed on (111)B (twinned and twin-free) as well as on (211)B epilayers can only be explained by the presence of impurities (acceptors and donors) in the epilayers. Although contamination during the MBE growth process cannot be completely disregarded there is a strong presumption that impurities are diffusing from the substrate. This hypothesis has not been tested in this program which has been suddenly disrupted due to a lack of funding (see attached letter)

In conclusion it is fair to say that in this program the Microphysics Laboratory has been successful in:

1) identifying the presence of microtwins in HgCdTe(111)B grown by MBE which are limiting device performance and yield,
2) determining their relation with the structural and electrical properties of the epilayer
3) understanding their formation mechanism

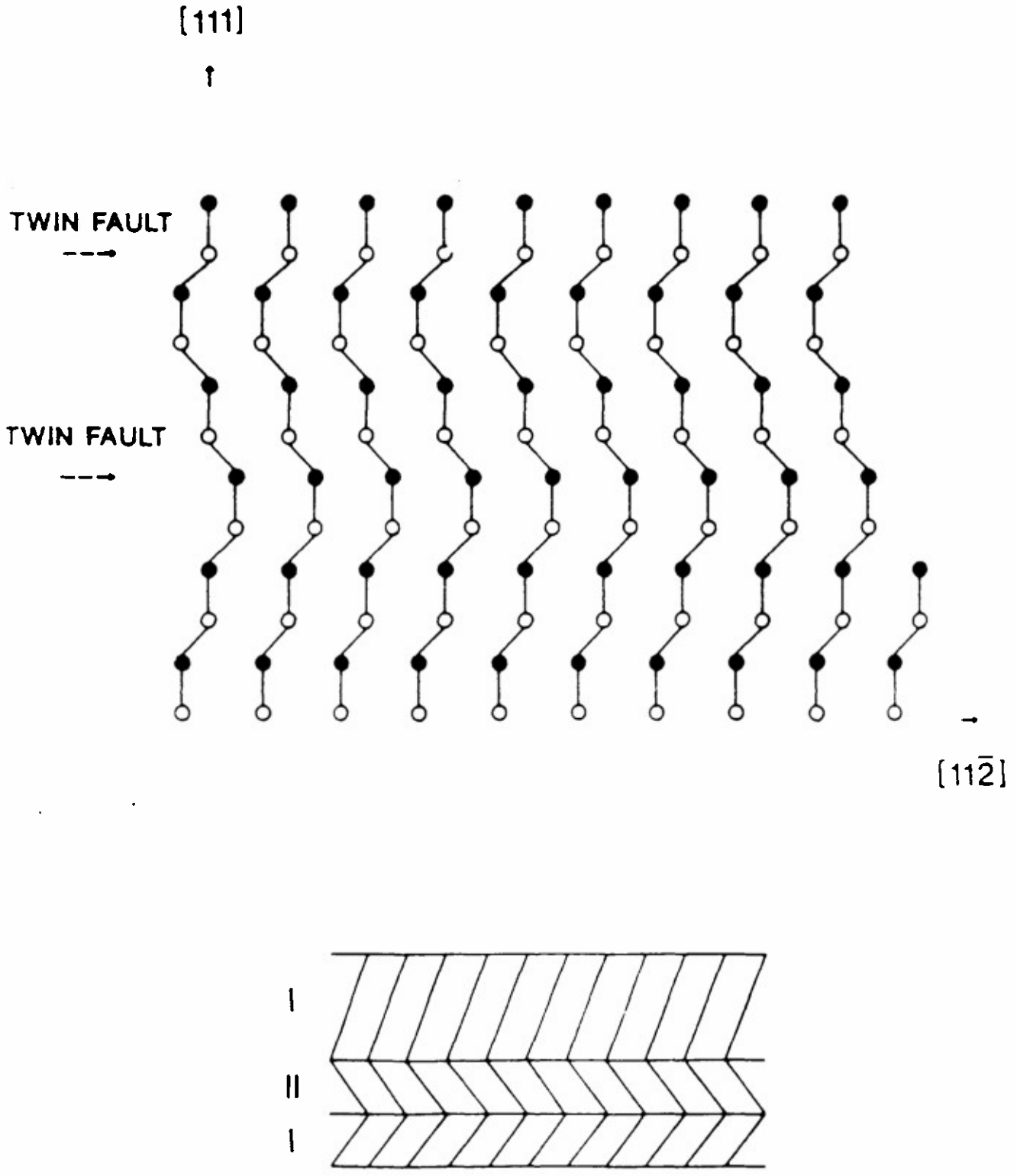

Fig. 1. Lamellar or stacking fault twin formed by a 180° rotation about the [111] direction.

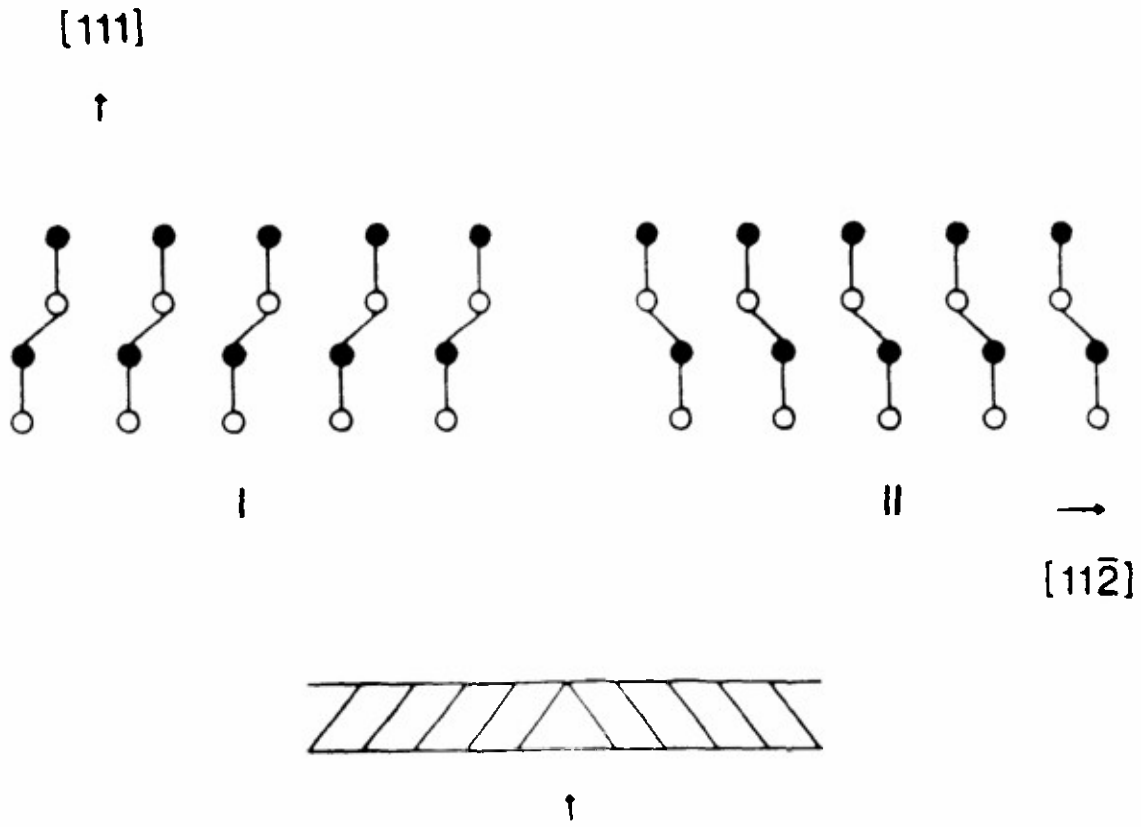

Fig. 2. Double positioning twin formed by a 180° rotation about the [111] direction.

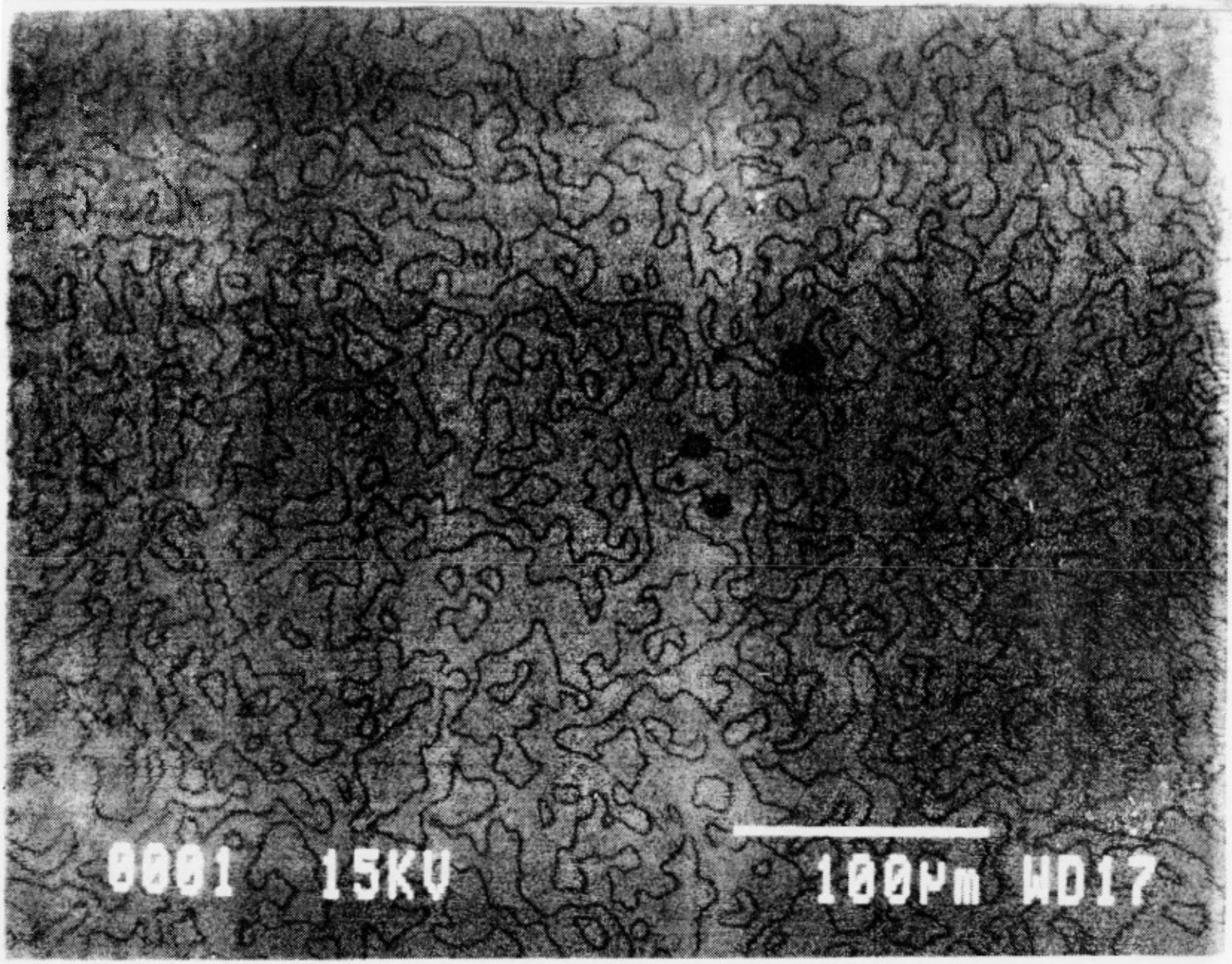

Fig. 3 Cathodoluminescence image of a twinned CdTe(111)B epilayer.

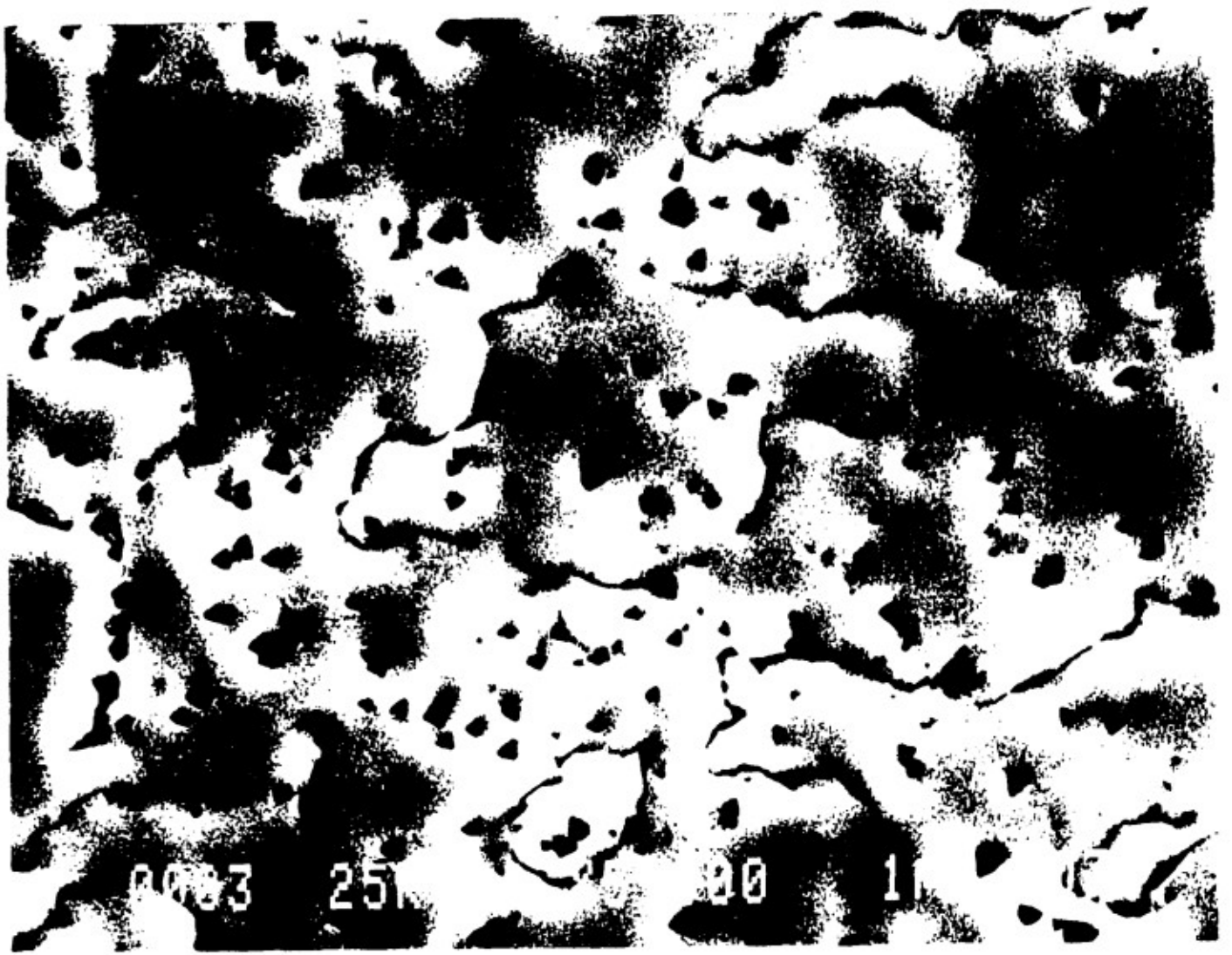

Fig. 4 Twinned (111)B HgCdTe layer after defect revealing etch.

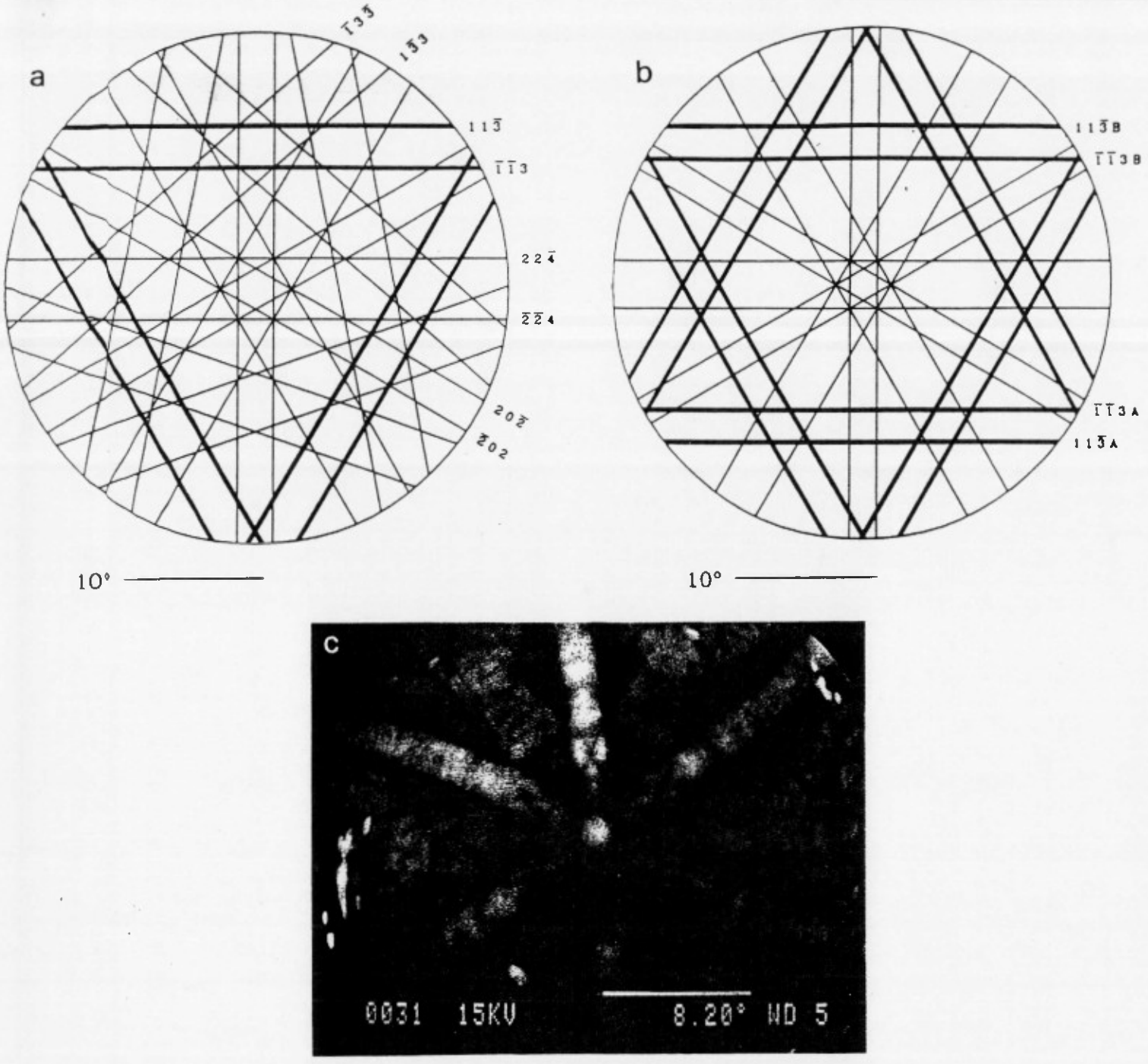

Fig. 5 Electron channeling pattern simulation of a CdTe crystal along the (111) axis: (a) twin-free crystal, 15.0 kV, fcc lattice, a=6.481 Å; (b) twinned crystal, 25.0 kV, fcc lattice, a=6.481 Å; (c) ECP pattern of a twinned CdTe crystal.

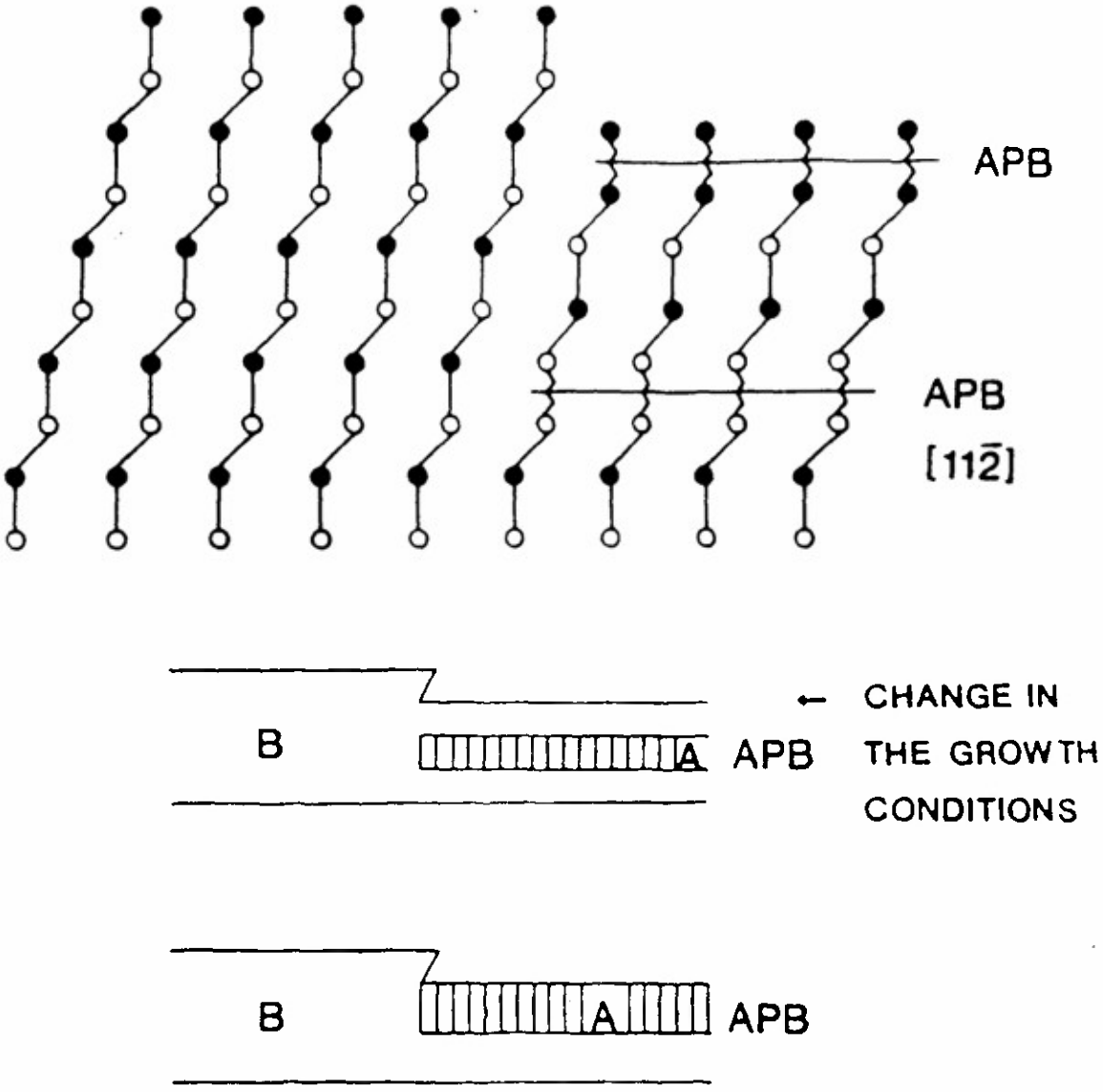

Fig. 6 Reflection twin formed by a mirror reflection with respect to the (111) plane.

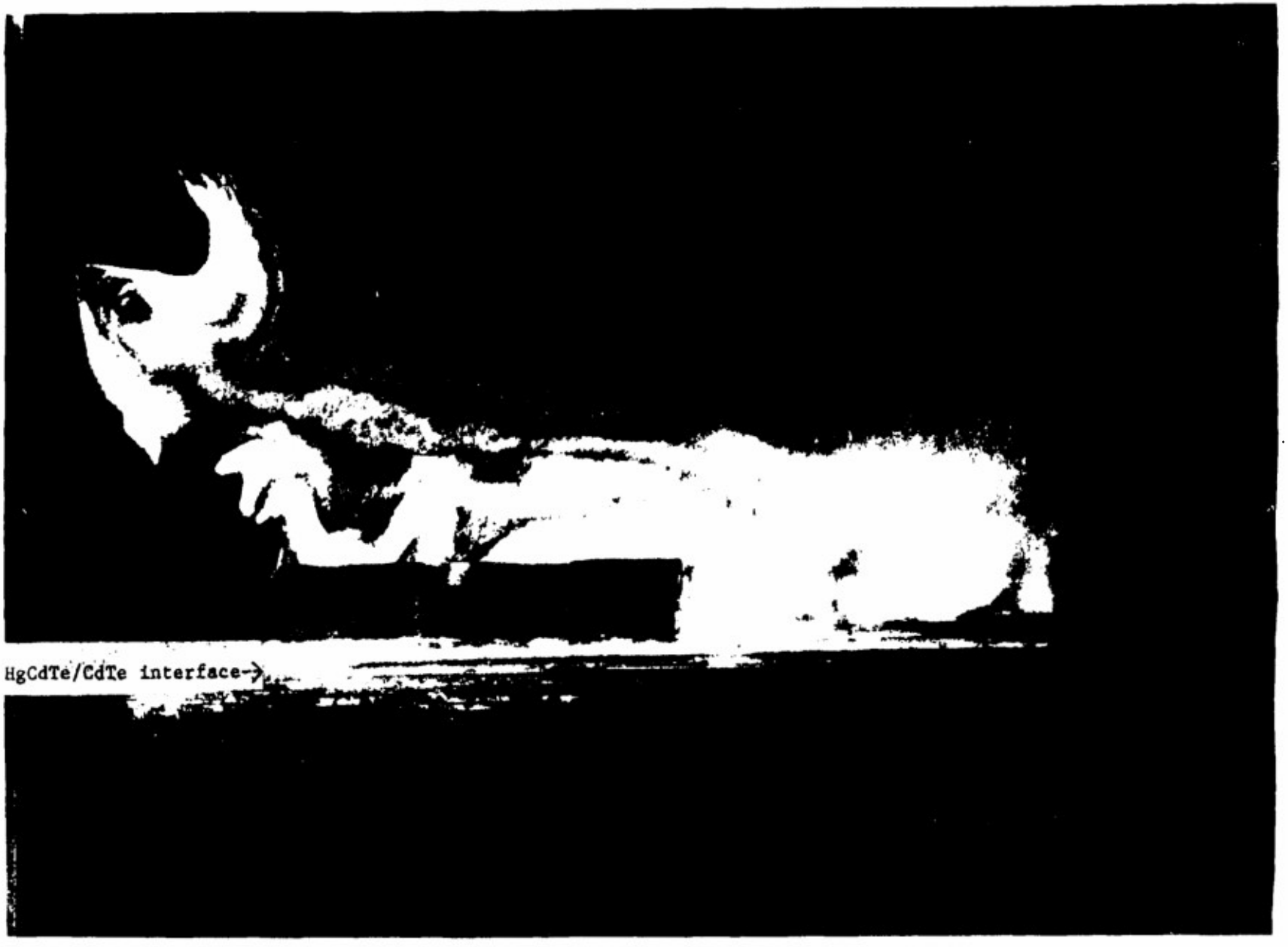

Fig. 7 Transmission electron microscopy of a HgCdTe(111)B/GaAs(100) substrate. Only CdTe epilayer exhibiting numerous lamellar twins and HgCdTe epilayer are visible.

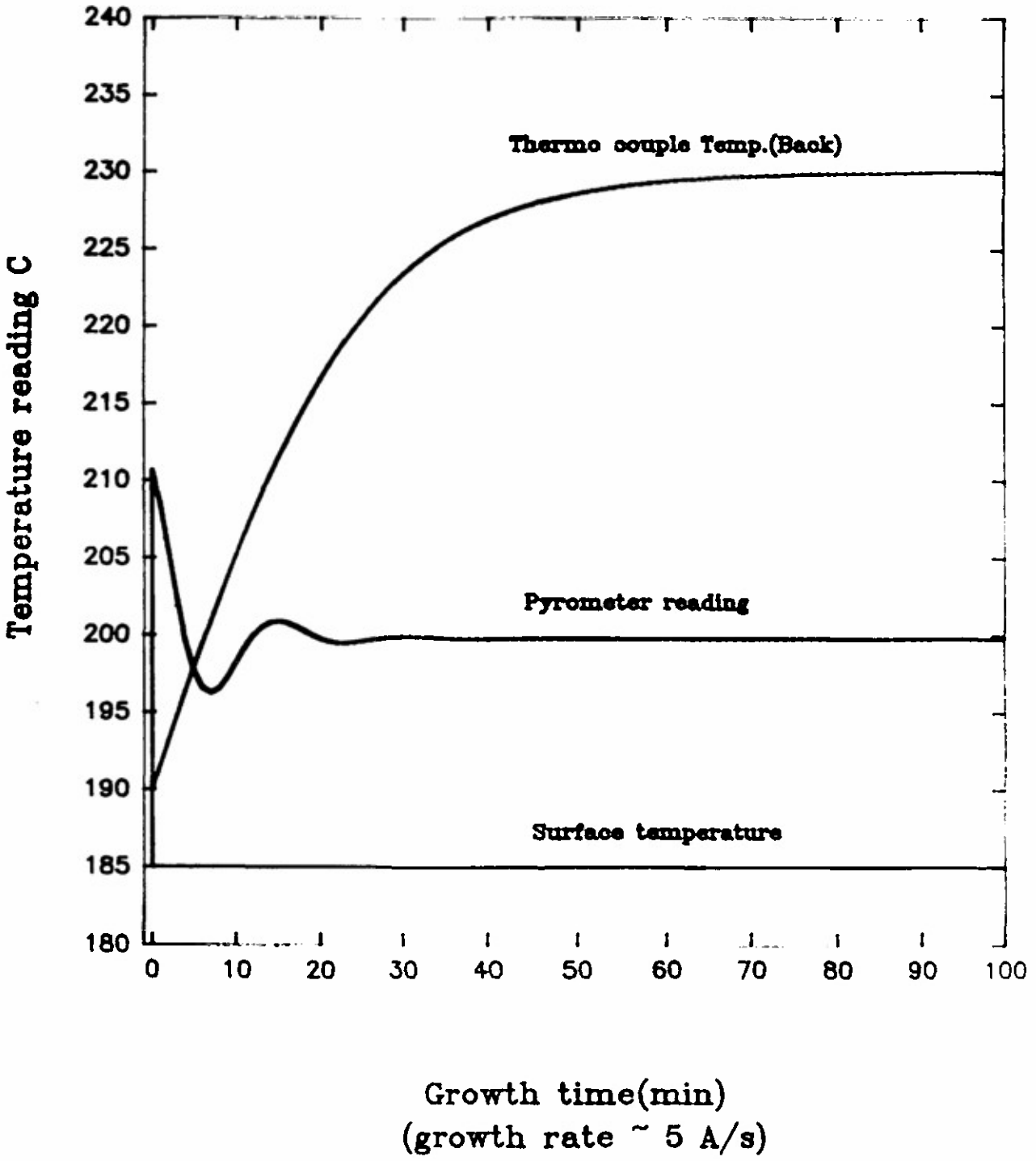

Fig. 8 Growth Temperature During MBE Growth of HgCdTe on CdZnTe

4) controlling and eliminating their formation through stringent control of the growth parameters, and

5) in formulating the hypothesis that impurities, very likely diffusing from the substrate, are present in the epilayer.

VIII. CONTRACT RELATED SCIENTIFIC ACTIVITY

1. Characteristics of p-n junctions fabricated on HgCdTe epilayers grown by MBE, Appl. Phys. Lett. 52, 2151 (1988).
2. New development on the control of homoepitaxial and heteroepitaxial growth of CdTe and HgCdTe by MBE, J. Cryst. Growth 111, 698 (1991).
3. MBE-IV International Conference, LaJolla (September 1990) J.P. Faurie (invited talk).
4. Ninth International Conference on Crystal Growth, Sendai, Japan (August 1989), J.P. Faurie (invited talk).
5. Effect of twinning in (111)B HgCdTe grown by MBE, 1989 MCT Workshop.

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DEPARTMENT OF THE ARMY
UNITED STATES ARMY LABORATORY COMMAND
ARMY RESEARCH OFFICE
P.O. BOX 12211, RESEARCH TRIANGLE PARK, NC 27709-2211

February 22, 1990

REPLY TO ATTENTION OF:
Physics Division

SUBJECT: Research Proposal No. 25133-PH entitled "The Influence of Defects in HgCdTe Grown by Molecular Beam Epitaxy (MBE) on Electrical Devices"

Professor Jean-Pierre Faurie
Department of Physics
The University of Illinois at Chicago
Chicago, Illinois 60680

Dear Professor Faurie:

As you may be aware, the Army's CNVEO has failed to provide the funds for the final increment on the above referenced contract. DARPA initially indicated they would increase their funding to cover CNVEO's missing portion. However, after repeated phone calls to Dr. Jim Murphy's office at DARPA, we have been unable to confirm this with DARPA.

The ARO budget was reduced significantly in FY90 and as a result the Physics Division has no available funds to cover this unexpected contingency. Consequently, your contract will be terminated without funding the final increment. We are fully cognizant of the disruption this sort of reprogramming can cause on research programs and personnel. Regretfully the Army Research Office has no options in this instance. This action is certainly no reflection on the excellent work performed under this research contract.

Thank you for your past research efforts on behalf of the Department of Defense, and we wish you the best of luck in finding continued support.

Sincerely,

David Skatrud
Physics Division